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(54) Title: METHOD AND DEVICE FOR MEASURING THE CONCENTRATION OF IONS IMPLANTED IN SEMICONDUCTOR MATERIALS

(57) Abstract

A method and apparatus that determines a concentration of ions implanted in a material is described. The method includes the steps of: (1) passing an excitation pulse through a diffracting mask (e.g., a phase or amplitude mask) to generate at least two excitation laser sub–pulses; (2) irradiating a region of the material with a "grating" pattern, formed by overlapping two excitation laser sub–pulses in time and space to initiate a time–dependent response (e.g., a change in refractive index) in the region; (3) diffracting a probe laser pulse having a duration that is at least as long as the time–dependent response off the region to generate a time–dependent signal beam; (4) detecting the time–dependent signal beam to generate a signal waveform; and (5) processing the signal waveform to determine the concentration of ions implanted in the material.

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METHOD AND DEVICE FOR MEASURING THE CONCENTRATION OF IONS IMPLANTED IN SEMICONDUCTOR MATERIALS

Background

This invention relates to measuring the
5   concentration of ions implanted in semiconductor
materials.

Most microelectronic devices (e.g., a
microprocessors) include a series of oxide, metal, and
semiconducting films grown or deposited on a
10   semiconducting substrate. The semiconducting substrate
is typically a single-crystal silicon wafer, while the
semiconducting films are typically an amorphous
"polysilicon" material containing small, crystalline
regions of silicon. Both silicon wafers and polysilicon
15   films are implanted with high-energy ions during
fabrication so that they exhibit a specified electrical
conductance. The implanted ions render silicon as being
"p" or "n" type. After implantation, both silicon and
polysilicon are annealed under high temperatures to heal
20   any lattice damage resulting from the implantation
process.

The electrical conductance of silicon and
polysilicon is affected by three properties of the
implanted ions: (1) atomic composition; (2) implantation
25   energy; and (3) ion concentration or dose. Silicon's
electrical conductivity is particularly dependent on the
concentration of the implanted ions. For example,
silicon wafers are typically implanted with arsenic,
argon, phosphorous, oxygen, or boron ions ranging in
30   concentration from 10^{10} - 10^{16} cm^{-3} to improve their
semiconducting properties. Polysilicon films are
implanted with similar ions at higher concentrations
(usually on the order of 10^{20} cm^{-3}) to function as
electrical conductors.

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The performance of a completed microelectronic device depends critically on the electrical properties of the silicon wafer and the overlying polysilicon films, and thus the ions implanted in these materials are
5 carefully monitored during fabrication. One property, called electrical sheet resistance, is measured by contacting a sample's surface with an electrical-testing instrument called a 4-point probe. Electrical current flowing from one probe to another depends on the
10 resistance of the material. Resistance, in turn, varies inversely with the concentration of implanted ions.

Ion concentration is also monitored using a non-contact, optical method that excites and detects an electron-hole plasma within the sample. The response of
15 the plasma is influenced by any damage in the semiconductor lattice resulting from the implanted ions. In this measurement, a first laser beam irradiates the semiconducting material and is partially absorbed to generate the electron-hole plasma. The plasma modifies
20 the reflectivity of the sample's surface and can therefore be measured with a second laser beam. The reflected beam is partially reflected by the sample and then analyzed to estimate the properties of the implanted ions.

25 Although used throughout the microelectronics industry, both 4-point probes and instruments that measure reflectivity suffer disadvantages. 4-point probes necessarily contact the sample, and are therefore destructive. This means that these instruments can only
30 measure "monitor" wafers or regions of "product" wafers that lack functioning devices. Instruments that monitor electron-hole plasmas by measuring reflectivity have limited use and generate signals that are difficult to interpret: they are mostly used to determine whether or

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not the sample has been ion implanted, rather than the
actual concentration of implanted ions.

Summary

The method and apparatus described herein measure
5   the concentration of ions implanted within a
semiconducting material with a non-contact, laser-based
technique called impulsive stimulated scattering (ISS).
ISS initiates and measures two different types of
responses, both of which depend on the concentration of
10   implanted ions: (1) time-dependent changes in the
sample's optical properties (i.e., complex refractive
index), referred to herein as an "electronic" response;
and (2) time-dependent acoustic phonons, referred to
herein as an "acoustic" response. Whether or not one or
15   both of the responses is measured depends on the sample
and the properties of the lasers used during ISS. For
example, ion-implanted samples containing silicon
typically exhibit an electronic response following
absorption of radiation during ISS. In this case,
20   optical absorption generates a time-dependent change in
the sample's refractive index, resulting in a response
that rapidly increases in amplitude and then decays away
with an exponential time constant. Both the decay
constant and amplitude of the response depend on the
25   concentration of the implanted ions. If the optical
wavelength used in ISS is very strongly absorbed (e.g.,
within a few hundred nanometers of the sample's surface),
an acoustic response results that includes coherent
acoustic phonons propagating through the lattice of the
30   ion-implanted semiconductor. In this case, the response
exhibits oscillations at a frequency that depends on the
concentration of the implanted ions.

ISS generates a signal waveform characterized by
one or both of the electronic and acoustic responses.

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The properties of the signal waveform are then analyzed to determine the concentration of the implanted ions. This concentration is then analyzed and used to control fabrication processes used to make microelectronic 5 devices.

In one aspect, the invention provides a method that determines a concentration of ions implanted in a material. The method includes the steps of: (1) passing an excitation pulse through a diffracting mask (e.g., a 10 phase mask) to generate at least two excitation laser sub-pulses; (2) irradiating a region of the material with a "grating" pattern, formed by overlapping two excitation laser sub-pulses in time and space to initiate a time-dependent response (e.g., a change in refractive 15 index) in the region; (3) diffracting a probe laser pulse having a duration that is at least long as the time-dependent response off the region to generate a time-dependent signal beam; (4) detecting the time-dependent signal beam to generate a signal waveform; 20 and (5) processing the signal waveform to determine the concentration of ions implanted in the material.

In embodiments, the processing step includes the step of comparing the signal waveform to a mathematical function, and then determining an amplitude of the 25 mathematical function to determine the amplitude of the signal waveform at a point in time. The mathematical function, for example, could be a function used to fit the signal waveform. In some cases, the mathematical function includes an exponential function, e.g., 30 $S_0(t_0) [Ae^{-(t + t0)/\tau}]$ or a derivative thereof, where A is the amplitude, τ is a decay constant, t is time, and S_0 is a unit step function starting at $t = t_0$. Once the amplitude is determined, the processing step can further include the step of comparing the amplitude to valves in a 35 database that correlates amplitudes of previously

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measured signal waveforms to concentrations of ions
implanted in representative materials. This comparison
determines the concentration of ions implanted in the
material. Alternatively, the analyzing step includes
5   analyzing the amplitude with a mathematical algorithm,
such as a first-principles calculation, to determine the
concentration of ions implanted in the material. For
example, the first-principles calculation could include
modeling the kinetics of the response of the sample to
10 determine the ion implant concentration. In other
embodiments, the processing step includes digitizing the
signal waveform to generate a data set, and then
determining the amplitude of the signal waveform at a
point in time by selecting a value from the data set. In
15 still other embodiments, the processing step can include
the steps of plotting the signal waveform as a function
of time, calculating the area underneath the plot, and
then comparing this value to a valve in a database
determine the concentration of implanted ions.
20   In typical applications, the sample is a
silicon-containing material, e.g., a polysilicon film or
a silicon wafer. Other materials that can be measured
include films and wafers containing gallium arsenide,
aluminum gallium arsenide, germanium, and derivatives and
25 analogs thereof. Other samples that can be measured
include ceramic materials, metals, and any other material
that can be implanted with ions. The ions that can be
implanted in these materials include ions of arsenic,
argon, boron, oxygen and phosphorous atoms.
30   In another aspect, the invention provides a method
for determining a concentration of ions implanted in a
silicon or polysilicon sample. The method includes the
steps of: 1) generating at least two excitation laser
sub-pulses; 2) irradiating a region of the material with
35 a grating pattern, formed by overlapping at least two

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excitation laser sub-pulses, to initiate a time-dependent, decaying, non-oscillatory response in the region; 3) diffracting a probe laser pulse, having a duration that is at least long as the time-dependent
5 response, off the region to generate a time-dependent signal beam; 4) detecting the time-dependent signal beam to generate a signal waveform; and 5) processing the signal waveform to determine the concentration of ions implanted in the silicon or polysilicon sample.

10   The method described above is carried out with an apparatus that includes: (1) an excitation laser for generating an excitation laser pulse; (2) a beam-delivery system including a diffracting mask for separating the excitation laser pulse into at least two sub-pulses and
15 then overlapping the sub-pulses in a region of the material to form a grating pattern; (3) a probe laser that generates a probe laser pulse that exceeds the duration of the time-dependent response and is oriented to diffract off the region to generate a time-dependent
20 signal beam; (4) a photodetector for detecting the time-dependent signal beam to generate a signal waveform; and (5) a processor (e.g., a computer) for processing the signal waveform as described above to determine the concentration of ions implanted in the material.

25   The diffracting mask, for example, can be a phase or amplitude mask containing a pattern of spatially varying opaque bars or transparent grooves.

The above-described method and apparatus have many advantages when compared to conventional techniques for
30 measuring the concentration of implanted ions. In general, ISS is an accurate, quantitative method for determining the concentration of ions implanted in both semiconductor substrates and thin films. The method is all-optical, non-contact, and non-destructive, and can
35 therefore measure semiconductor materials used in actual

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devices (i.e., production samples), rather than monitor
samples. This information can then be used by
manufacturers to improve both the yield and performance
characteristics of microelectronic devices containing
5 these materials.

The apparatus for making ISS measurements is
compact, easily automated, and collects signal waveforms
having very high signal-to-noise ratios. In particular,
the diffracting masks, and particularly the phase masks,
10 simplify the alignment of the excitation and probe laser
beams and allow the grating pattern to be changed in a
rapid, facile manner. This arrangement forms a grating
pattern that maximizes the signal waveform amplitude for
a particular material to be rapidly and easily selected.
15 The phase mask also eliminates the need for additional
beam-delivery optics, such as additional lenses and
beamsplitters, that are normally required for ISS
measurements. Likewise, use of a probe pulse having a
duration that exceeds the time-dependent response allows
20 the user to collect (and then average) entire signal
waveforms with a single laser shot. This significantly
reduces the time required to measure high-quality data
and further eliminates the need for additional
data-collection optics, such as a mechanical delay line
25 for delaying a probe pulse relative to the excitation
pulses.

Measurements with the above-mentioned apparatus
are made rapidly (typically requiring only a few seconds)
and with high spatial resolution (typically using a probe
30 beam having a spot size of about 25 microns or less).
Thus, small features of the sample, such as a small-scale
test site of a microelectronic device or an area near a
wafer's edge, can be easily measured. Moreover, the
above-mentioned apparatus can be incorporated into a
35 facile, compact, easy-to-use instrument that can be

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employed in a microelectronic-device fabrication
facility. The instrument, for example, can be attached
to a production tool and used to make *in situ*
measurements of an ion-implantation process.

5   Still other advantages will be apparent from the
following detailed description, and from the claims.

Brief Description of the Drawings

          Fig. 1 is a schematic drawing of the ISS method;

          Fig. 2 is a graph of a time-dependent signal
10 waveform characterized by an electronic response measured
from a 2-micron, ion-implanted polysilicon film deposited
on a silicon wafer;

          Figs. 3A-3B are graphs of two-dimensional,
49-point contour maps of, respectively, the amplitude (in
15 mV) of a signal waveform measured with ISS and sheet
resistance (in normalized units) measured with a 4-point
probe from a 2-micron polysilicon film deposited on a
100-mm diameter silicon wafer;

          Figs. 3C-3D are graphs of, respectively, the
20 amplitude (in mV), and sheet resistance (in normalized
units), values from Figs. 3A-3B plotted for each point in
the 49-point map;

          Figs. 4A-4C are graphs of the signal waveform
amplitude (in mV) vs. the log of ion implant
25 concentration measured from a set of ion-implanted
silicon wafers implanted with, respectively, ions
implanted at 50, 80, and 110 KeV.;

          Figs. 5A and 5B are graphs of the signal waveform
amplitude (in mv) vs. log of ion implant concentration
30 measured from silicon wafers implanted, respectively,
with ions at 110 and 160 KeV;

          Figs. 5C and 5D are graphs of the acoustic
frequency (in MHz) vs. log ion implant concentration

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measured from silicon wafers implanted, respectively, with 110 and 160 KeV;

Fig. 6 is a graph of time-dependent signal waveforms characterized by an acoustic response measured from silicon wafers implanted with, respectively, 10^{16} (bottom) and 5×10^{16} (top) arsenic ions cm^{-3}; and

Fig. 7 is a schematic drawing of an optical system for measuring the concentration of ions implanted in a sample using ISS.

Detailed Description
Method for Measuring Ion Implantation Concentration with ISS

Referring to Fig. 1, the concentration of ions implanted in a sample 10 (e.g., silicon) is measured with an optical, laser-based technique 11 called impulsive stimulated scattering (ISS). Applicants have described the use of a related laser-based technique, called ISTS, to measure other material properties in MEASUREMENT OF MATERIAL PROPERTIES WITH OPTICALLY INDUCED PHONONS (U.S. Patent 5,633,711); SIMPLIFIED DEVICE AND METHOD FOR TIME-RESOLVED OPTICAL MEASUREMENTS (U.S.S.N. 08/377,310, filed January 24, 1995); METHOD AND DEVICE FOR MEASURING FILM THICKNESS (U.S.S.N. 08/783,046, filed July 15, 1996); and IMPROVED METHOD AND APPARATUS FOR MEASURING MATERIAL PROPERTIES USING TRANSIENT GRATING SPECTROSCOPY (U.S.S.N. 08/855,555 filed June 30, 1997). These references are therefore incorporated herein by reference.

In ISS, a pair of optical pulses 12', 12'' from an excitation laser (not shown in the figure) separated by an angle θ are overlapped in time and space in a region 15 on the sample's surface. The optical pulses 12', 12'' typically have a duration of between 0.3 and 0.7 nanoseconds (i.e., 0.3 and 0.7 x 10^{-9} seconds), an energy of about 5 microjoules/pulse, and a wavelength that is absorbed by the sample; for silicon, the wavelength is in

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either the visible or infrared spectral region. Inter-
ference between the overlapped pulses 12', 12'' forms a
spatially varying "grating" pattern 15 containing alter-
nating "light" (constructive interference) 17 and "dark"
5   (destructive interference) 19 regions. Radiation is
absorbed by the sample 10 in the light regions 17, but
not in the dark regions 19 of the grating pattern. The
absorbed radiation initiates both time-dependent acoustic
and electronic responses having properties that depend on
10 the concentration of the ions implanted in the sample 10.
These responses are measured in their entirety by ir-
radiating a region near the grating pattern 15 with a
probe pulse 20. The probe pulse 20 has a duration (typi-
cally several hundred microseconds) that is longer than
15 both the electronic and acoustic responses and a peak
power of several hundred milliwatts; the wavelength of
the probe pulse is typically in either the visible or
infrared spectral regions. The probe pulse is partially
reflected to form a reflected beam 20', and partially
20 diffracted to form a pair of signal beams 25', 25'' that
are the +1 and -1 diffracted orders. One or both of the
signal beams 25', 25'' is detected with a photodetector
(not shown in the figure) to generate a signal waveform.
The signal waveform is then analyzed to determine the
25 concentration of the implanted ions.
          Whether or not the sample's response is
electronic, acoustic, or both depends in part on how
strongly the radiation in the light regions of the
grating pattern 15 is absorbed by the sample. For
30 example, silicon has a band gap near 900 nm: radiation
having an energy above the band gap (e.g., visible
radiation) is therefore absorbed over a shorter
pathlength than radiation having an energy below the band
gap (e.g., radiation at 1 micron). An electronic
35 response typically results when the excitation radiation

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has an energy that is above or slightly below the band
gap. Without being bound to any theory, it appears that
in this case ISS generates excited-state charge carriers
(e.g., electron-hole pairs) in the light regions, but not
5 the dark regions of the grating pattern. The density of
charge carriers depends on the concentration of ions
implanted in the sample. Once generated, the charge
carriers have a finite lifetime and recombine with a time
constant on the order of several nanoseconds. During
10 this period the sample's refractive index in the light
regions is temporarily changed relative to the refractive
index in the dark regions. This results in a spatially
periodic variation in refractive index (i.e., a phase
grating) that diffracts the probe radiation during the
15 lifetime of the charge carriers. An increase in the
concentration of implanted ions will increase the number
of excited charge carriers and, consequently, the dif-
ference in refractive index between the light and dark
regions of the grating pattern. This, in turn, increases
20 the intensity of the diffracted probe beam and the
amplitude of the ISS signal waveform.

To verify this explanation, data were collected at
a number of different grating patterns, each having a
different spatial frequency. The decay time constants
25 describing these data showed no dependence on the grating
pattern, indicating that the signal waveform was not due
to a diffusive process (e.g., thermal diffusion).

An acoustic response results from
radiation-induced heating generated by ISTS. This
30 technique has been described in detail in MEASUREMENT OF
MATERIAL PROPERTIES WITH OPTICALLY INDUCED PHONONS (U.S.
Patent 5,633,711); SIMPLIFIED DEVICE AND METHOD FOR
TIME-RESOLVED OPTICAL MEASUREMENTS (U.S.S.N. 08/377,310,
filed January 24, 1995); and METHOD AND DEVICE FOR
35 MEASURING FILM THICKNESS (U.S.S.N. 08/783,046, filed July

15, 1996). Briefly, during ISTS excitation radiation is absorbed by the sample in the light regions of the grating pattern during the short duration of the excitation pulse. These regions then undergo a rapid

5 thermal expansion to launch counter-propagating acoustic waves having a wavelength and orientation that match the spatial properties of the grating pattern. Acoustic waves oscillate at a frequency that is determined by their wavelength and the acoustic properties of the

10 sample (i.e., the density and longitudinal and transverse sound velocities). The concentration of implanted ions increases the stiffness of the host lattice and therefore affects these properties. During the measurement, the acoustic frequency of the ISTS-excited acoustic wave is

15 thus measured to determine the concentration of the implanted ions. In this case, the acoustic response is optimized when the excitation radiation is strongly absorbed over a relatively short (e.g., a few hundred nanometers) pathlength in the sample. For silicon and

20 polysilicon, this means that the excitation radiation typically has a wavelength in the visible or ultraviolet portion of the spectrum.

Figs. 2 and 5 show signal waveforms (30 in Fig. 2; 31 and 32 in Fig. 5) characterized, respectively, by

25 electronic (Fig. 2) and acoustic (Fig. 5) responses. The data in Fig. 2 were measured from a 2-micron polysilicon film deposited on a 100-mm silicon wafer. The film was implanted with an average concentration of approximately 10^{20} cm^{-3} arsenic ions and then annealed to heal any damage

30 to the polysilicon. Measurements were made with ex-citation pulses having a wavelength of 1.064 microns, a duration of about 0.5 nanoseconds, and an energy of about 3.5 microjoules/pulse from a Nd:YAG laser. The excitation pulses were generated by passing a single

35 excitation laser beam through a phase mask. The probe

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laser had a wavelength of 860 nm, a pulse duration of 200 microseconds, and a peak power of 200 mW. As is clear from the data, the signal waveform has a well-defined decaying component but no oscillating component,

5   indicating an electronic response. The waveform decays from a value of about 40 mV at 20 nanoseconds to a value of about 10 mV at 60 nanoseconds. This decay is accurately fit with a single-exponential fitting function 32 having the form $S_0(t_0)[Ae^{-(t + t_0)/\tau}]$, where A is the

10 amplitude of the fit (in units of mV) and τ is the decay constant (in units of nanoseconds). S_0 is a unit step function starting at $t = t_0$. The fit to the signal waveform 30 was generated with a conventional fitting algorithm that iteratively adjusts the parameters of the

15 fitting function 32 (i.e., S_0, A, t_0, and τ described above) until this function best matches the signal waveform. The amplitude value A is then determined from the fitting function and further analyzed to determine the ion implantation concentration.

20   Fig. 3A shows how the concentration of implanted ions varies across the polysilicon film. Data for this figure were measured by determining the amplitude of the signal waveform at 49 separate points distributed in a standard, radial pattern . Data were acquired using the

25 instrument described above. The points are contained in three equally spaced concentric rings, with the first point in the center of the wafer, points 2-8 in the first ring, points 9-25 in the second ring, and points 26-49 in the third ring. Amplitudes (A) measured from signal

30 waveforms at each point on the sample are plotted in a contour format using a linear interpolation algorithm. The time constant (τ) was roughly the same for each signal waveform.

          As shown in Fig. 3A, the amplitude of the signal

35 waveform varies smoothly and systematically across the

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surface of the polysilicon sample; the variations are
both large and highly repeatable. The signal waveform
amplitude is maximized near the bottom, central portion
of the polysilicon film (x = 0 mm, y = -50 mm) and
5   decreases systematically from the bottom portion to the
top portion of the water Fig. 3C shows the same data in
a different format, with the amplitudes of the signal
waveforms measured for Fig. 3A plotted as a function of
the points in the 49-point contour map. Each point is
10 indicated by a square in the figure. These data show the
smooth, systematic variation of the data for the
different points in the map, with the regions having
relatively high ion implant concentrations yielding
amplitudes in the range of 40-50 mV, and the regions of
15 relatively low ion implant concentrations yielding
amplitudes in the range of 5-15 mV. The regions of
relatively high and low amplitudes correspond to
concentrations of approximately 10^{21} cm^{-3} and 10^{19} cm^{-3} ,
respectively.
20   The same polysilicon film was measured with a
4-point probe to verify that the amplitude of the ISS
waveform is, in fact, representative of the concentration
of ions implanted in the polysilicon. As described
above, the 4-point probe measures electrical sheet
25 resistance, a well-known property that is inversely
related to the concentration of implanted ions. Fig. 3B
shows a 49-point contour map of the normalized, inverse
sheet resistance measured in a concentric-ring pattern
similar to that used in Fig. 3A. Similarly, Fig. 3D
30 shows the data plotted in a point-by-point format like
Fig. 3C. Comparing these figures indicates that the ISS
and 4-point probe data correlate quite well, both showing
a "distribution of implanted ions that is maximized near
the bottom, center portion of the polysilicon sample and
35 decreases towards the top, central portion of the sample.

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Comparison between Figs. 3C and 3D show that the ISS data
have, in general, a higher signal-to-noise ratio than the
4-point probe data. Discrepancies between the contours
of Figs. 3A and 3B exist because the two experiments
5   measure slightly different points on the polysilicon
sample and are susceptible to different types of factors
(e.g., impurities, surface quality, substrate effects)
that may result in error.

Data similar to that shown in Figs. 2 and 3A-3F
10 were also measured from similar 2-micron polysilicon
films that were not annealed. As before, the data were
characterized by an electronic response that was highly
repeatable and could be fit with a single-exponential
function. Like that shown above for the annealed film,
15 the data for the un-annealed film varied smoothly and
systematically across the wafer and depended on the con-
centration of implanted ions.

In a separate set of experiments, electronic
responses were measured from a set of 100-mm diameter
20 silicon wafers implanted with argon ions at different
enregics. Figs. 4A-4C show the signal waveform amplitude
measured plotted as a function of ion implant
concentration for three different silicon wafers having
concentrations ranging from 10^{12}-10^{16} cm^{-3}. The implant
25 energy for each of these samples ranged from 50-110 keV.
The data were measured from a center point of each wafer
using ISS and the same instrument used to measure the
polysilicon samples.

Signal waveforms measured from each sample
30 exhibited an electronic response similar to that measured
from the polysilicon samples. In this case, the signal
amplitude was determined by calculating the area
underneath the signal waveform. Figs. 4A-4C each show
that the signal waveform amplitude increases
35 systematically with the log of the concentration of

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implanted ions for each of the implantation energies.
The dependence of the amplitude on the log of
implantation concentration is basically linear to each
implantation energy.

5   Data like that shown in Figs. 4A-4C can be stored
in a database and later accessed to determine
quantitatively the concentration of ions implanted in a
sample during an actual fabrication process. In a
particular example, data (i.e., signal waveform amplitude
10   vs. ion implant concentration) from a set of test samples
having a systematically varying concentration of implant-
ed ions are generated and verified with electrical
testing instruments, such as a 4-point probe. These data
are then stored in a database on a computer. When ISS
15   measurements are made on actual product samples during
fabrication the amplitude of the signal waveforms are
determined by fitting the data as described above. The
resulting amplitude is then compared to values in the
database to determine quantitatively the concentration of
20   implanted ions.

          Figs. 5A and 5B show how the ISS signal amplitude
varies with ion implantation concentration for relatively
high-energy, low-concentration implantation processes
(i.e., less than 10^{12} ions/cm^3 and implantation engeries
25   at 110 and 160 eV). The data shown in these figures are
consistent with that shown in Figs. 4a-4C, and indicate
an increase in ISS signal amplitude with increasing
concentration.

          ISS can also measure an acoustic response, like
30   that shown in Fig. 2B, that correlates to the
concentration of implanted ions. Fig. 6 shows two signal
waveforms 31, 32 measured from different 8-inch silicon
wafers implanted with arsenic ions at concentrations of,
respectively, 10^{14} and 5×10^{14} cm^{-3}. Both signal waveforms
35   exhibit an oscillating, acoustic response. The signal

waveforms shown in these figures were measured using ISS
and an excitation pulse having a wavelength of 532 nm, a
pulse duration of 0.2 nanoseconds, and an energy of about
5 microjoules/pulse. The probe pulse had a wavelength of
5 514 nm, a pulse duration of 200 microseconds, and a peak
power of 100 mW. Inspection of Fig. 5 indicates the
signal waveform 32 measured from the sample implanted
with 5×10^{14} cm^{-3} includes an electronic response
characterized by an exponential decay during the first 5
10 nanoseconds, and an acoustic response that oscillates and
decays over a time period of about 70 nanoseconds. The
frequency of oscillation for the acoustic responses
measured from this sample is approximately 550.5 MHz.
The signal waveform 31 measured from the sample implanted
15 with 10^{16} ions includes a comparable acoustic response but
a relatively weak electronic response. The frequency of
oscillation for the acoustic responses measured from this
sample is approximately 550 MHz. Larger differences in
frequency are expected when the excitation pattern is
20 adjusted to excite a higher acoustic frequency.

Figs. 5C and 5D show consistent results measured
from silicon wafer implanted with ions at high energies
and low concentrations. In this case, the acoustic
frequency was measured to be about 592 MHz for both the
25 100 KeV and 160 KeV samples implanted at 10^{10} $ions/cm^{-3}$.
This acoustic frequency decreased to about 584 MHz for
the sample implanted with ions at 110 KeV and 10^{12} cm^{-3},
and to about 588 MHz for ions at 160 KeV and 10^{12} cm^{-3}.

As described above, the dependencies of both the
30 electronic and acoustic responses on ion concentration
can be calibrated using a well-defined set of test
samples to generate a database. Once the relationship
between frequency and ion implant concentration is
determined, measurements from actual product wafers can

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be compared to the database to determine the ion
implantation concentration.

Apparatus for Determining Ion Implant Properties Using ISS
       Fig. 7 shows an optical system 50 for measuring
5 the properties of an ion-implanted sample 10 using ISS.
A similar system suitable for making these measurements
is described in SIMPLIFIED DEVICE AND METHOD FOR
TIME-RESOLVED OPTICAL MEASUREMENTS (U.S.S.N. 08/377,310,
filed January 24, 1995), and IMPROVED METHOD AND
10 APPARATUS FOR MEASURING MATERIAL PROPERTIES USING
TRANSIENT GRATING SPECTROSCOPY (U.S.S.N. 08/855,555 filed
June 30, 1997).
       The system 50 includes an excitation laser 52 that
initiates the acoustic and electronic responses, and a
15 probe laser 54 that measures these responses. The
optical properties of the excitation and probe lasers are
described in reference to Fig. 1, above. The excitation
laser, for example, can be a Nd:YAG laser or similar
laser operating at a fundamental or harmonic wavelength.
20 The probe laser can be a modulated diode laser. Both the
excitation and probe lasers run at matched repetition
rates that are typically in the range of 100-1000 Hz.
       The excitation laser 52 generates a pulse 12 that
is collimated with a first collimating lens 60 and then
25 focused onto a phase mask 62 with a cylindrical lens 64.
A portion of the pulse 12 is reflected by a glass cover
slip 65 and detected with a low-speed photodetector 67 to
generate an electrical pulse for triggering a
data-acquisition system (not shown in the figure). The
30 phase mask 62 includes a series of patterns 66, each of
which generates a different grating pattern 15 on the
sample 10. After impinging a pattern 66 on the phase
mask 62, the excitation pulse 56 is diffracted into two
sub-pulses 12', 12'' which diverge at an angle θ

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determined by the pattern 66. Higher order diffracted
beams are typically filtered out with a beam block (not
shown in the figure). The diverging sub-pulses 12', 12''
are collected with a first imaging lens pair 70 that
5   focuses and overlaps them onto the surface 49 of the
sample 10 to form the grating pattern 15. The first
imaging lens 70 is positioned so that the grating pattern
15 has the same periodicity as the pattern 66 on the
phase mask 62. Different grating patterns can be formed
10 simply by translating the phase mask 62 so that a new
pattern is irradiated with the incident excitation pulse
12.

The probe laser 54 generates a probe pulse 20 that
is collimated with a second collimating lens 55 and
15 focused on the grating pattern 15 with a second spherical
lens 71 to measure the electronic and acoustic responses
of the ion-implanted sample 10. As described above, the
electronic or acoustic (or both) responses diffract a
portion of the probe pulse 20 to form a signal beam 25.
20 A beam-stop 81 blocks a reflected portion of the probe
beam 20. A second imaging lens 76 collects the signal
beam 74 and focuses it into a high-speed (e.g., 1 GHz)
photodectector 80. This generates a light-induced
electrical signal which is then analyzed with a computer
25 (not shown in the figure) to determine the concentration
of ions implanted in the sample.

The spatial dimensions of the excitation
sub-pulses 12', 12'' and probe pulse 20 focused onto the
sample are chosen to maximize the amplitude of the signal
30 waveform. The excitation sub-pulses are typically
overlapped to form an elliptical grating pattern, with
the long and short axes of the ellipse being between 150
and 25 microns, respectively. The distance between light
and dark regions in the pattern is typically between 5
35 and 15 microns. The probe pulse is typically focussed to

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a spot that lies completely within the grating pattern.
For example, the probe pulse can be focussed to a round
spot with a diameter of less than 25 microns.

Ion-Implanted Materials

5   The above-describe method and apparatus can
determine the concentration of ions implanted in
different types of host samples. These samples include
semiconducting materials, such as silicon-containing
(e.g. polysilicon) films, silicon wafers, and films and
10   wafers containing gallium arsenide, aluminum gallium
arsenide, germanium, and derivatives and analogs thereof.
Other samples that can be measured include ceramic
materials, metals, and any other material that can be
implanted with ions.
15   Implanted ions that can be measured include
arsenic, argon, boron, oxygen, phosphorous, and any other
ion which can alter the electrical properties of a host
material.

Other Embodiments

20   Other embodiments are within the scope of the
above-describe method and apparatus. For example,
different optical systems, such as one including a
different lens configurations as that described above, an
amplitude mask in place of the phase mask, or a
25   beamsplitter in place of the phase mask, can be used.
        In another optical system, described in IMPROVED
METHOD AND APPARATUS FOR MEASURING MATERIAL PROPERTIES
USING TRANSIENT GRATING SPECTROSCOPY (U.S.S.N. 08/855,555
filed June 30, 1997), three sub-pulses, rather than two,
30   are used to excite the sample through ISS. In this
application, the three sub-pulses are equally spaced in a
linear fashion (i.e., the center, right, and left beams)
prior to being imaged onto the sample. When focused with

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a lens, the center beam propagates down a central optical
axis of the beam-delivery system, while the right and
left beams converge toward the same spot at the same
angle but on opposite sides of the center beam. The
5 beams are overlapped on the sample to form the transient
grating that excites electronic or acoustic processes in
the sample.

In general, any optical system for performing ISS
or ISTS is suitable. Likewise, excitation and probe
10 lasers that have suitable optical properties can be used
in place of the lasers described above.

In other embodiments the signal waveform is
processed by plotting it and then determining the area
underneath the plot. This area is then compared to
15 values in a database to determine the ion concentration.
In other embodiments, the signal waveform is fit with a
more complex function than that described above, such as
a bi-exponential function that includes a relatively
"fast" time constant and a relatively "slow" time
20 constant. In this case, either the fast or slow time
constant may be analyzed to determine the concentration
of implanted ions. In still other embodiments,
mathematical algorithms, such as algorithms based on
kinetic modeling of a charge-carrier system, can be
25 developed to relate the concentration of implanted ions
to an amplitude or frequency contained in the signal
waveform. Such algorithms would obviate the need for a
database to determine the ion concentration.

Still other embodiments are within the scope of
30 the following claims.

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What is claimed is:

1. A method for determining a concentration of
ions implanted in a material, comprising the steps of:
    passing an excitation pulse through a diffracting
5 mask to generate at least two excitation laser
sub-pulses;
    irradiating a region of the material with a
grating pattern, formed by overlapping at least two
excitation laser sub-pulses, to initiate a time-dependent
10 response in the region;
    diffracting a probe laser pulse, having a duration
that is at least long as the time-dependent response, off
the region to generate at least one time-dependent signal
beam;
15   detecting at least one time-dependent signal beam
to generate a signal waveform;
    processing the signal waveform to determine the
concentration of ions implanted in the material.

2. The method of claim 1, wherein the processing
20 step includes the steps of:
    comparing the signal waveform to a mathematical
function that represents the signal waveform; and
    determining an amplitude of the mathematical
function to determine the amplitude of the signal
25 waveform at a point in time.

3. The method of claim 2, wherein the
mathematical function includes an exponential function.

4. The method of claim 3, wherein the exponential
function is $S_0(t_0) [Ae^{-(t + t0)/\tau}]$ or a derivative thereof,
30 wherein A is the amplitude, τ is a decay constant, t is
time, and S_0 is a unit step function starting at $t = t_0$.

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5.   The method of claim 1, wherein the processing step further includes comparing the amplitude of the signal waveform to a database that correlates amplitudes of previously measured signal waveforms to concentrations
5   of ions implanted in materials to determine the concentration of ions implanted in the material.

6.   The method of claim 1, wherein the processing step further includes analyzing the amplitude with a mathematical algorithm to determine the concentration of
10 ions implanted in the material.

7.   The method of claim 1, wherein the processing step includes digitizing the signal waveform to generate a data set and then determining the amplitude of the signal waveform at a point in time by selecting a value
15 from the data set.

8.   The method of claim 1, wherein the processing step includes determining an area covered by a plot of the signal waveform.

9.   The method of claim 8, wherein the processing
20 step further includes comparing the area to a database that correlates the area with the concentration of ions implanted in a material to determine the concentration of ions implanted in the material.

10.   The method of claim 1, wherein the probe
25 laser beam comprises a laser pulse.

11.   The method of claim 10, wherein the laser pulse has a duration that exceeds the duration of the time-dependent response.

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12. The method of claim 1, wherein the diffracting mask is a phase or amplitude mask.

13. The method of claim 1, wherein the material contains silicon.

14. The method of claim 13, wherein the material is a polysilicon film.

15. The method of claim 13, wherein the material is a silicon wafer.

16. The method of claim 1, wherein an ion implanted in the material is an ion of atoms selected from the group consisting of arsenic, argon, boron, and phosphorous atoms.

17. The method of claim 1, wherein the processing step further includes the steps of processing the signal waveform to determine a frequency, and analyzing the frequency to determine the concentration of ions implanted in the sample.

18. A method for determining a concentration of ions implanted in a silicon or polysilicon sample, comprising the steps of:
    generating at least two excitation laser sub-pulses;
    irradiating a region of the material with a grating pattern, formed by overlapping at least two excitation laser sub-pulses, to initiate a time-dependent, decaying, non-oscillatory response in the region;

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diffracting a probe laser pulse, having a duration that is at least long as the time-dependent response, off the region to generate a time-dependent signal beam;

detecting the time-dependent signal beam to
5   generate a signal waveform; and

processing the signal waveform to determine the concentration of ions implanted in the silicon or polysilicon sample.

19.   An apparatus for determining a concentration
10   of ions implanted in a semiconducting material, comprising:

an excitation laser for generating an excitation laser pulse;

a beam-delivery system comprising a phase mask for
15   separating the excitation laser pulse into at least two sub-pulses and then irradiating a region of the material with a grating pattern formed by overlapping at least two sub-pulses to initiate a time-dependent response in the region;

20   a probe laser for generating a probe laser pulse having a duration that is at least as long as the time-dependent response and an orientation such that the probe pulse diffracts off the region to generate a time-dependent signal beam;

25   a photodetector for detecting the time-dependent signal beam to generate a signal waveform; and

a processor for processing the signal waveform to determine the concentration of ions implanted in the material.

30   20.   The apparatus of claim 19, wherein the diffracting mask is a phase mask or amplitude mask.

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21. The apparatus of claim 19, wherein the processor is a computer that compares the signal waveform to a mathematical function and determines the amplitude of the signal waveform at a point in time by determining
5 an amplitude of the mathematical function.

22. The apparatus of claim 19, wherein the processor is a computer that analyzes the amplitude of the signal waveform and compares the amplitude to a database to determine the concentration of ions implanted
10 in the material.

23. The apparatus of claim 19, wherein the processor is a computer that determines the area covered by the signal waveform and compares the area to a database to determine the concentration of ions implanted
15 in the material.

FIG. 1

2-Micron Polysilicon on Silicon
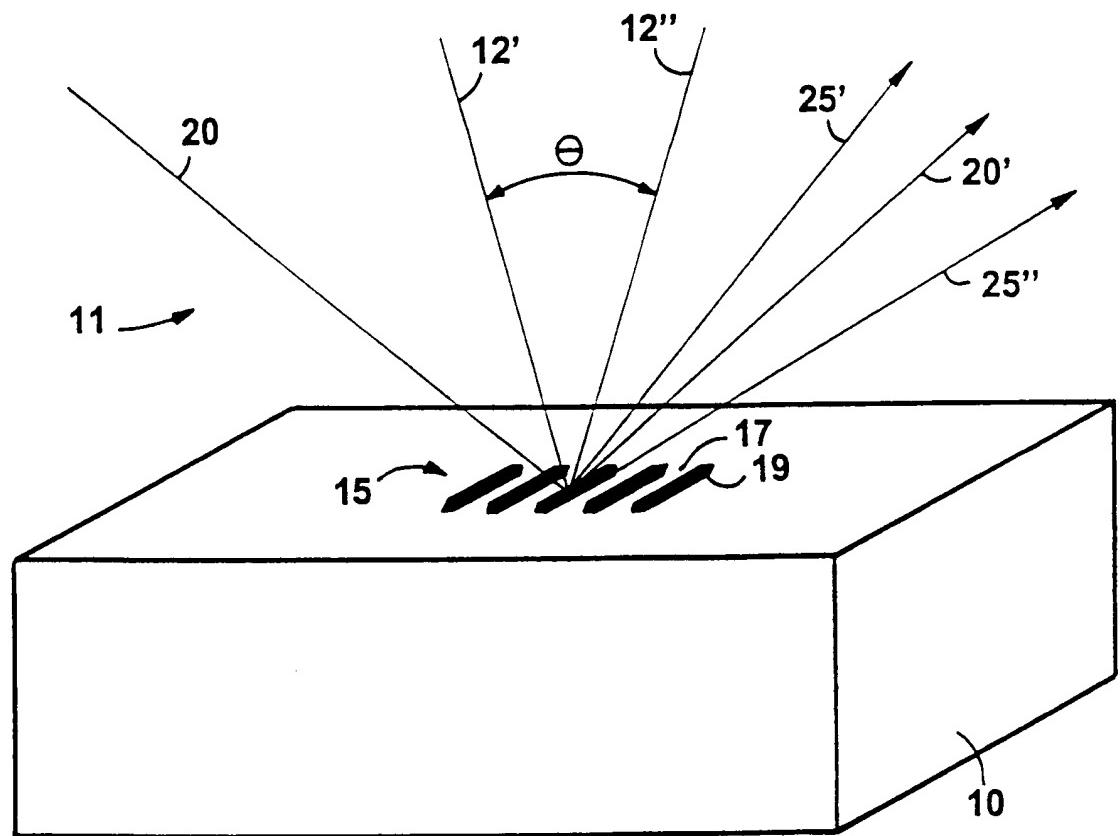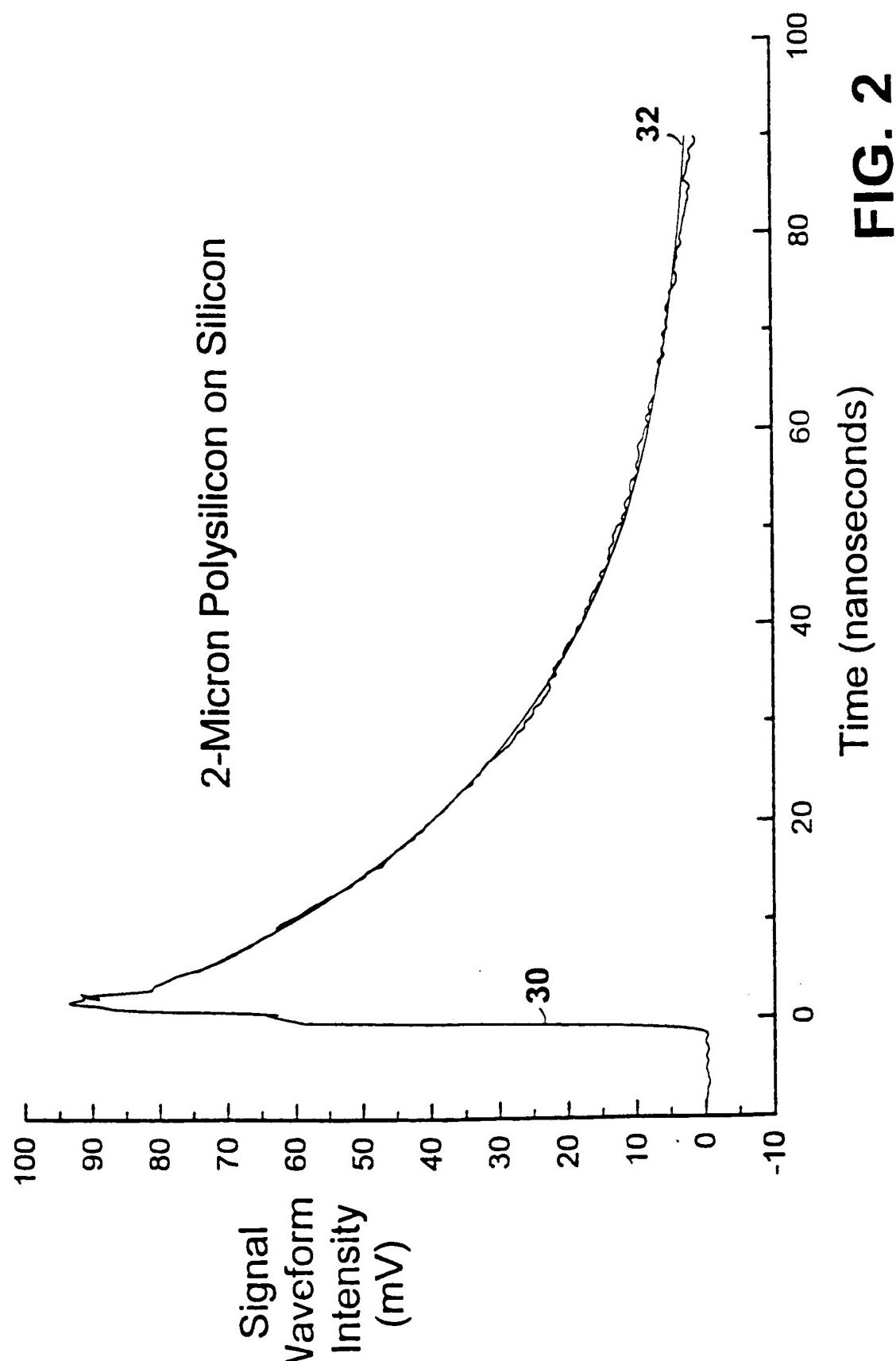
FIG. 2

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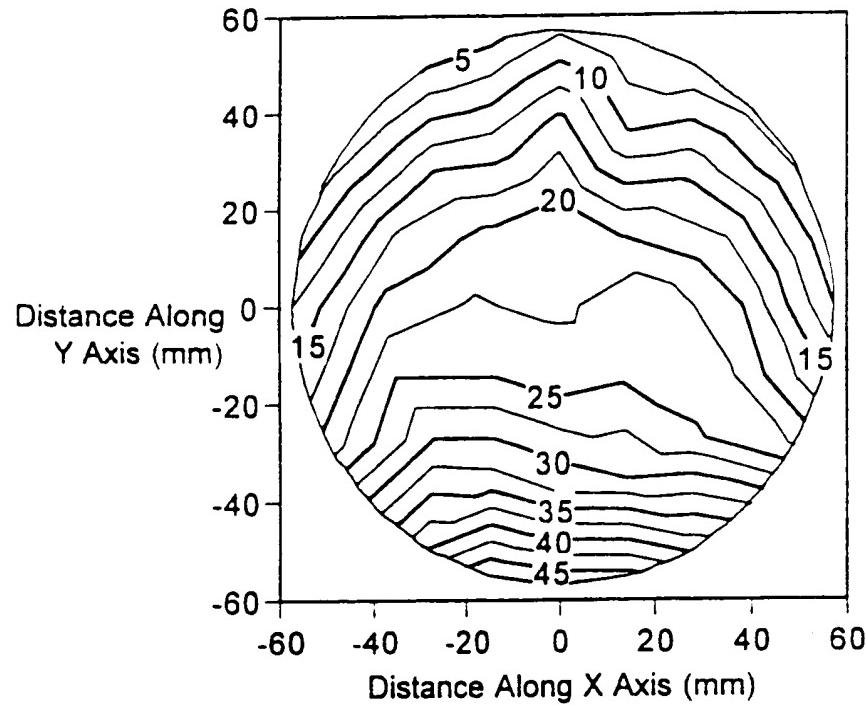
FIG. 3A

FIG. 3B

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FIG. 3C
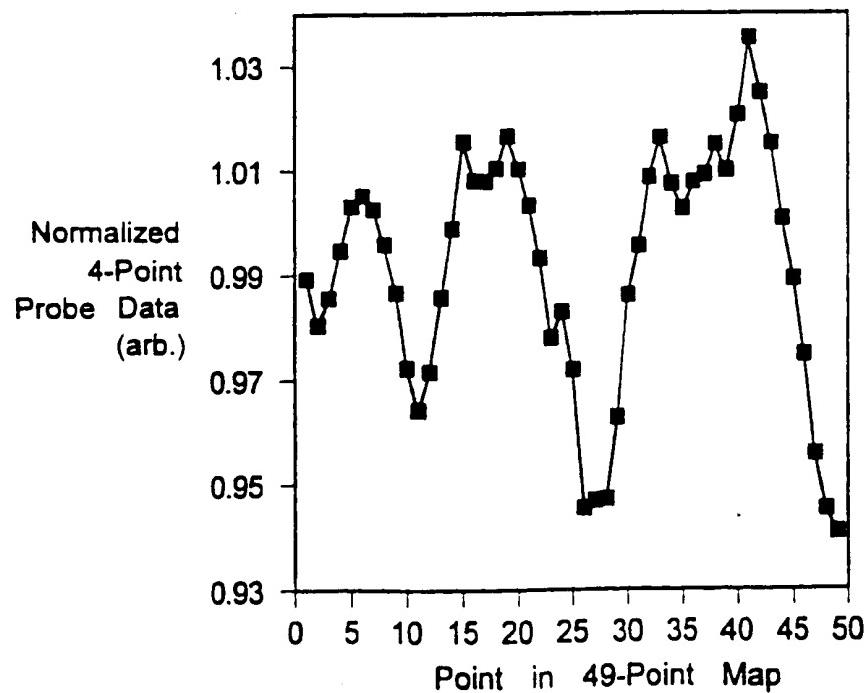
FIG. 3D
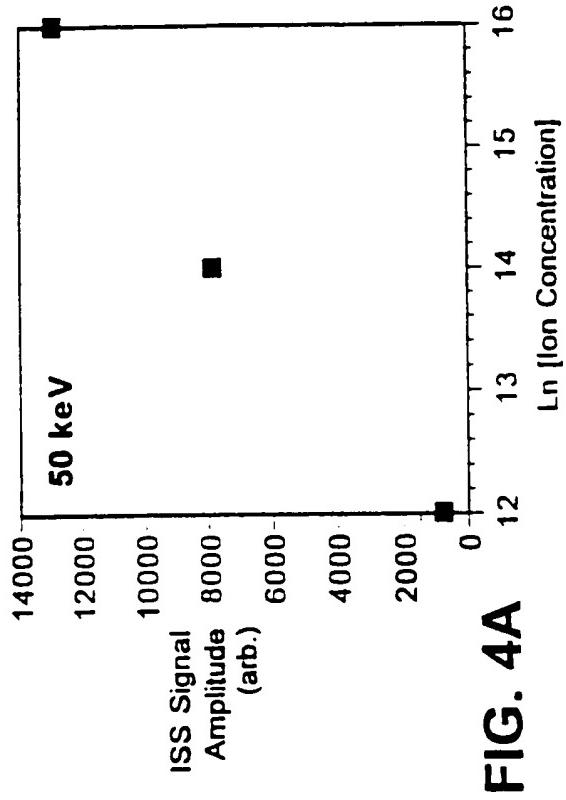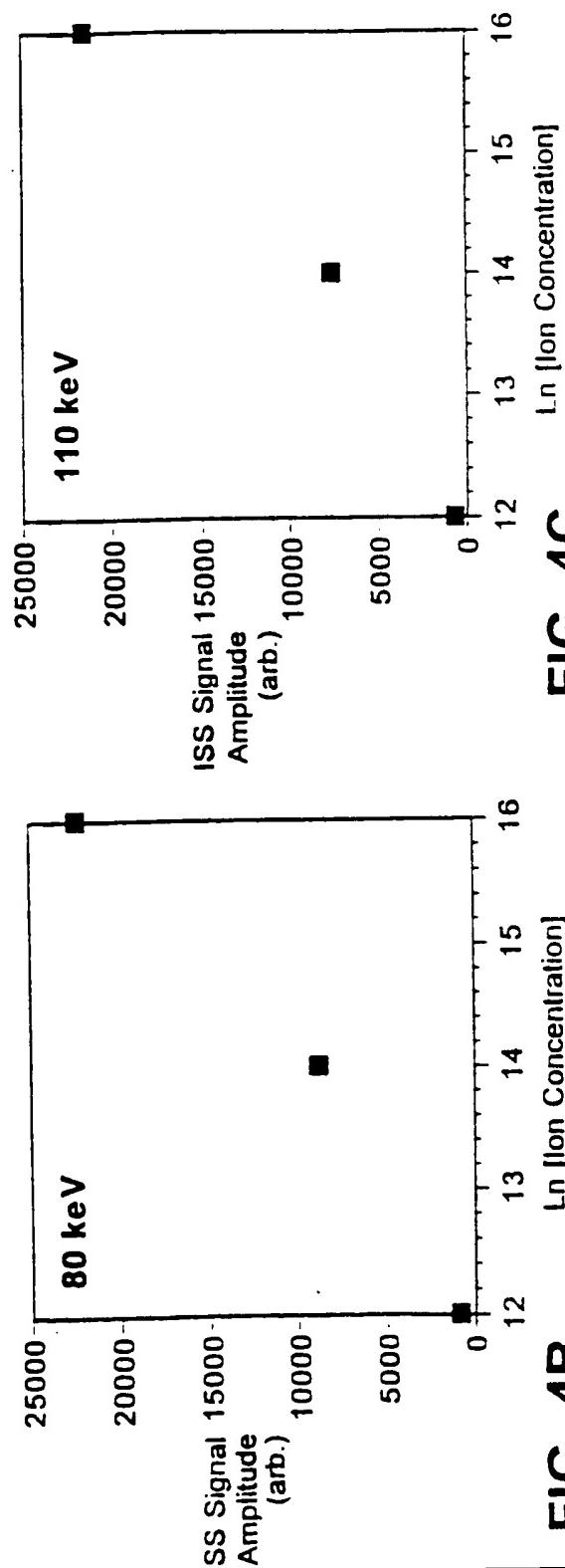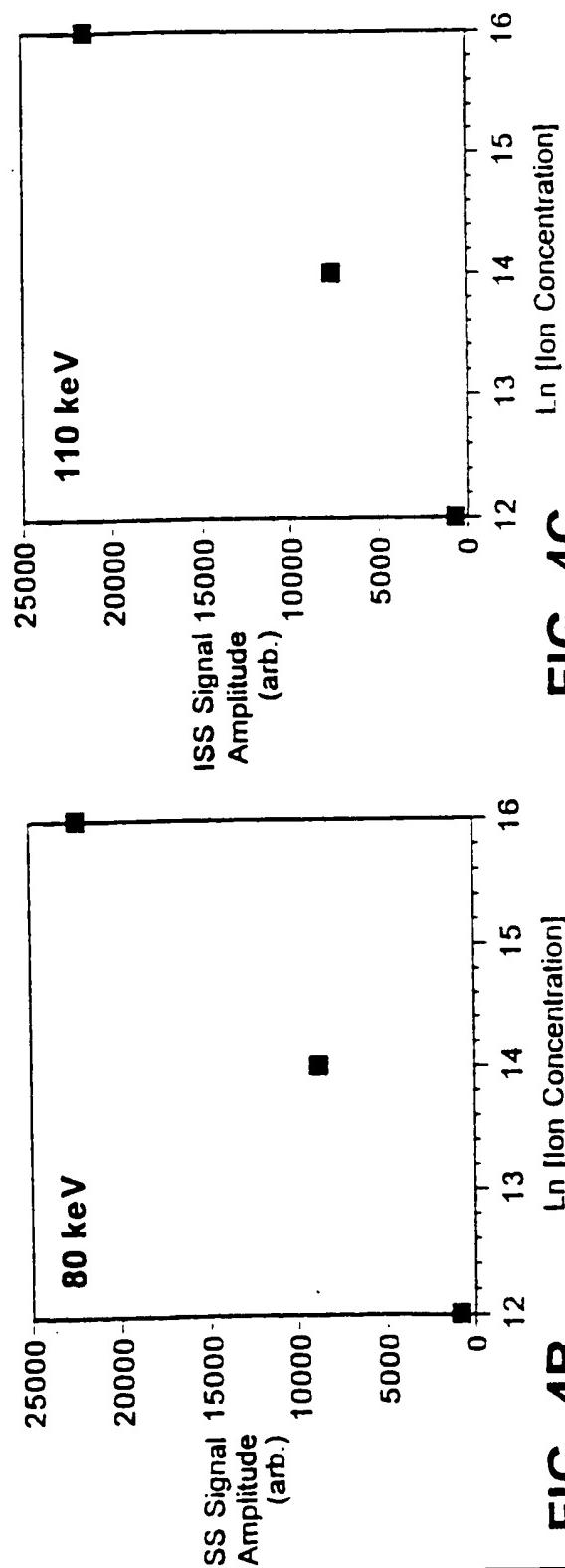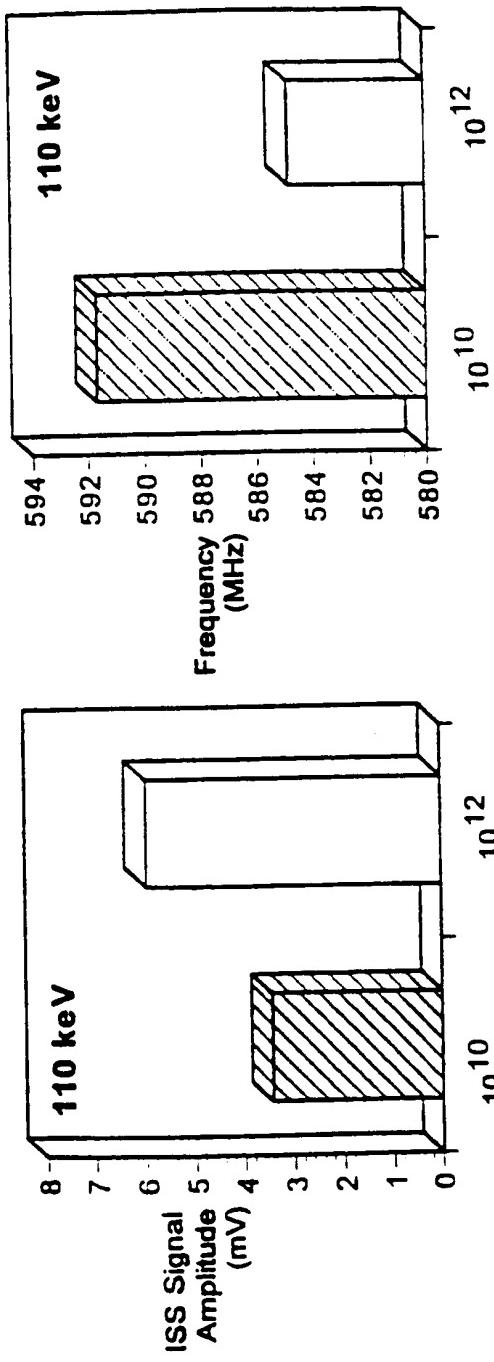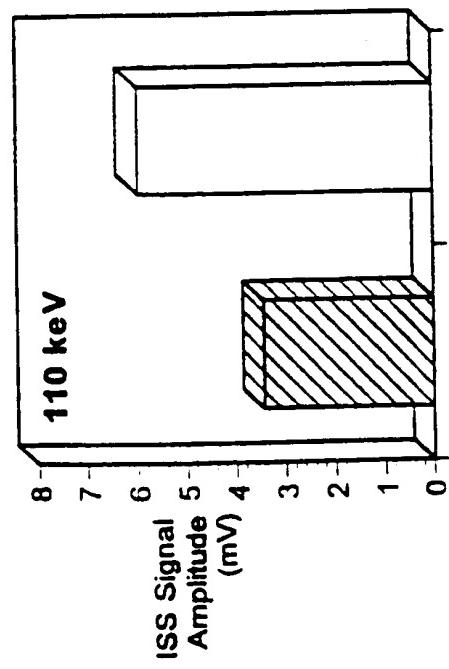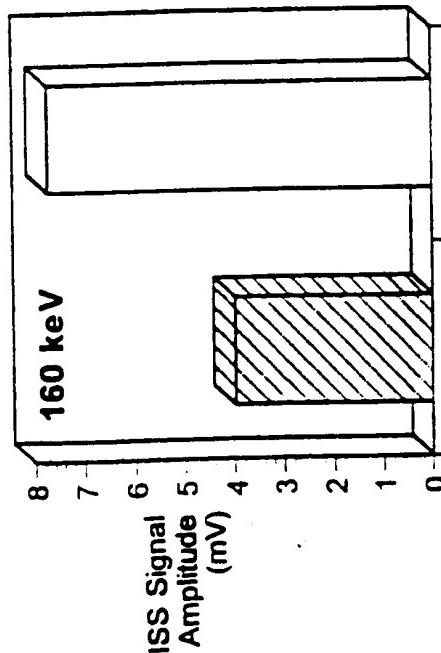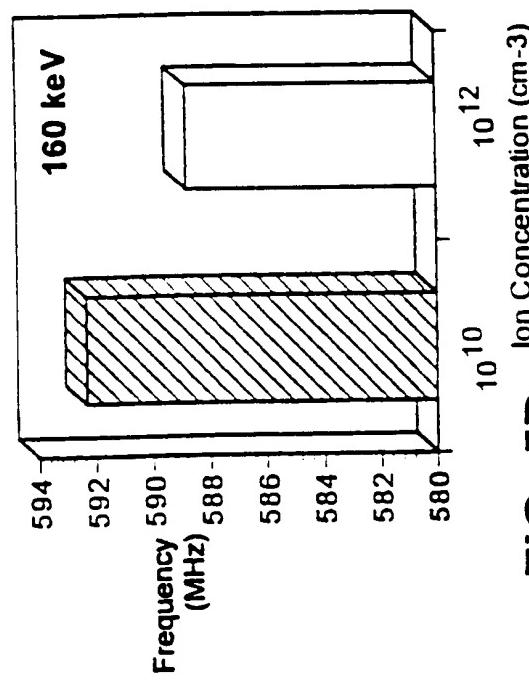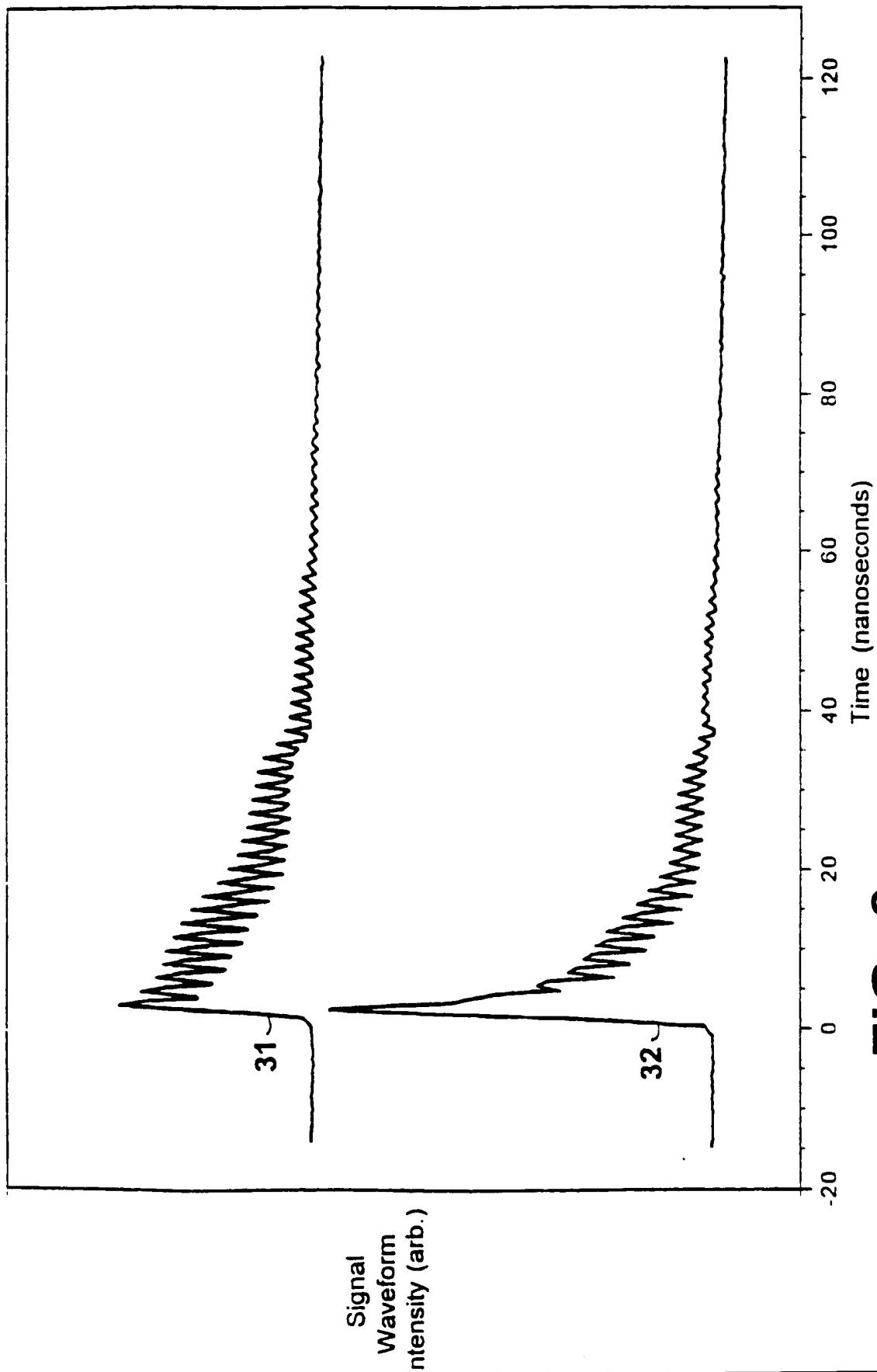
FIG. 4A

FIG. 4B

FIG. 4C

Electronic

110 keV

FIG. 5A

Electronic

160 keV

FIG. 5B

Acoustic

110 keV

FIG. 5C

160 keV

FIG. 5D

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FIG. 6
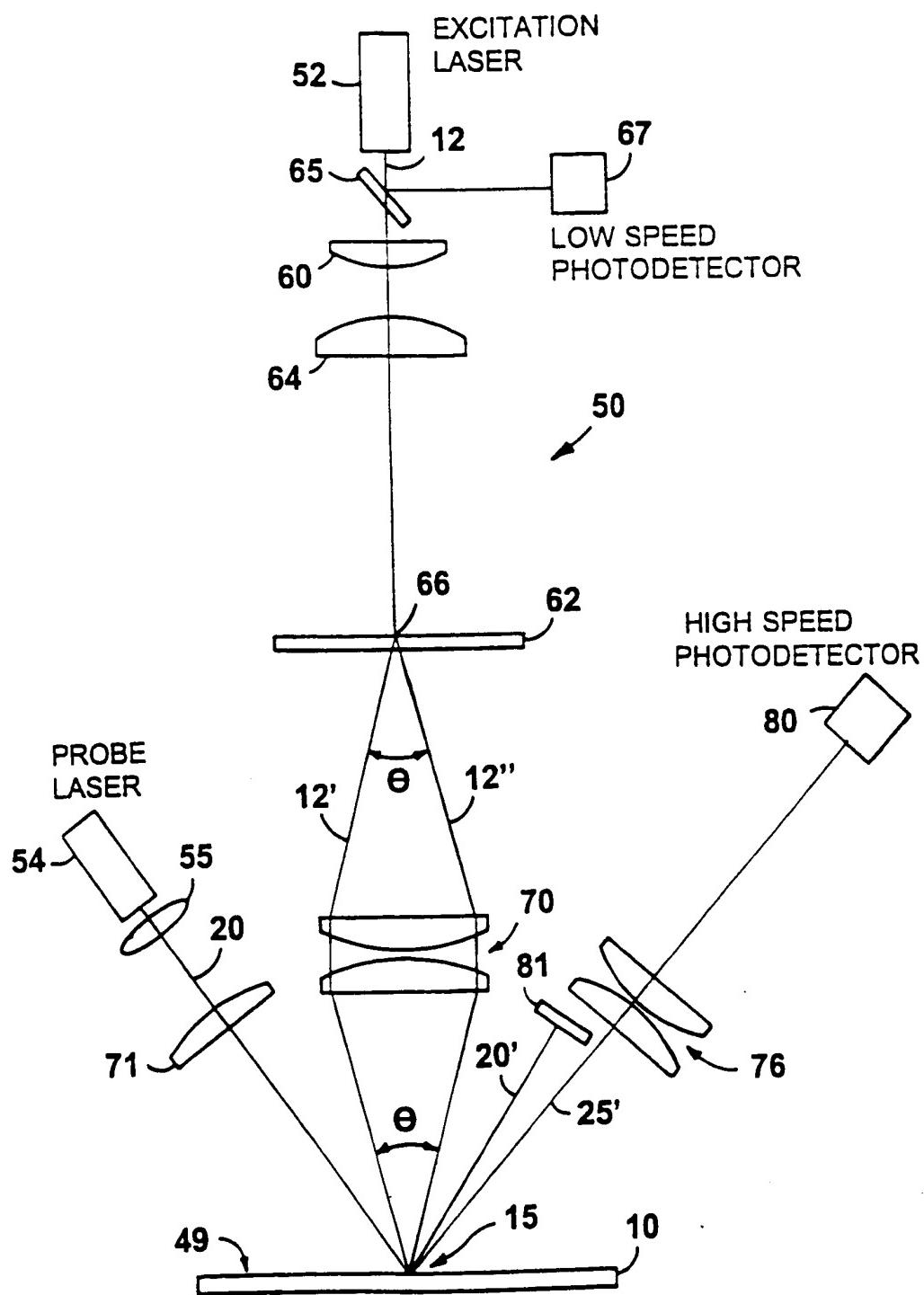
FIG. 7

A.	CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01B 09/02
US CL :356/432

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/432, 432T, 356

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPTO APS: diffraction grating, wave, probe and excitation source, time dependent

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US 5,734,470 A (ROGERS et al) 31 March 1998 (31/03/98) SEE ENTIRE DOCUMENT	1-23

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	
"E"	earlier document published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	
"P"	document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 AUGUST 1998	0 2 SEP 1998

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT	ROBERT KIM